VENTILATION STRATEGIES FOR U.S. MANUFACTURED HOMES

by

Andrew K. Persily and Samuel R. Martin
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899 USA

Reprinted from the International Society of Indoor Air Quality and Climate, Proceedings of the Healthy Buildings 2000 Conference. Volume 2, August 6-10, 2000. Espoo, Finland, p. 291-296.

NIST CENTENNIAL 1901-2001

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

VENTILATION STRATEGIES FOR U.S. MANUFACTURED HOMES

Andrew K. Persily. Samuel R. Martin

National Institute of Standards and Technology, USA

ABSTRACT

The HUD Manufactured Home Construction and Safety Standards contain requirements intended to provide adequate levels of outdoor air ventilation in U.S. manufactured homes. In the implementation of these standards, questions have arisen regarding the impact and significance of some of these requirements. Some of these questions relate to the actual ventilation rates in homes built to the standards and the means of providing supplemental mechanical ventilation to meet the standard's requirements. Other questions concern how specific ventilation system components such as duct leakage, local exhaust fans and air inlets affect ventilation rates, air movement patterns, and building pressures. In order to obtain some insight into these issues, the multizone airflow and indoor air quality program CONTAM was used to simulate a double-wide unit under several different ventilation scenarios. These scenarios include envelope infiltration only, infiltration plus the effects of local exhaust and forced-fan operation, an outdoor air intake duct installed on the forced-air return, and whole house exhaust with and without passive inlet vents. Simulations were performed to predict outdoor air ventilation rates into the house due to infiltration and mechanical ventilation, airflow rates between the rooms, building pressures, and ventilation air distribution. Annual simulations were performed in three cities to assess ventilation rates and energy consumption associated with these scenarios. The results show that despite the assumption in the HUD standards that infiltration contributes 0.25 h^{-1}, the predicted infiltration rates are lower than this value for many hours of the year. The supplemental ventilation systems investigated in this study provide ventilation rates that meet or exceed the total ventilation requirement of 0.35 h^{-1}, but the impacts of such systems are dependent on their operating schedules. The results of these simulations are presented and discussed, and recommendations are made for changes to the HUD standards and the ventilation of manufactured homes.

KEYWORDS: air change rate, infiltration, modeling, residential, standards, ventilation

INTRODUCTION

The HUD manufactured home standards, referred to as the Manufactured Home Construction and Safety Standards (MHCSS), cover the design and construction of all manufactured homes in the United States and contain a number of requirements related to ventilation [1]. Since these standards have been issued, questions have arisen regarding the ventilation-related requirements and their implementation. This paper briefly summarizes the results of a study addressing some of these questions [2].

The ventilation requirements in the MHCSS state that each home shall be capable of providing a minimum air change rate of 0.35 h^{-1}, corresponding to the residential ventilation requirement in ASHRAE Standard 62-1999 [3]. The MHCSS also states that infiltration and exfiltration shall be considered to provide an air change rate of 0.25 h^{-1}. The standard then states that the remaining 0.10 h^{-1} may be provided by mechanical or passive systems or a

Proceedings of Healthy Buildings 2000
Volume 2. August 6-10, 2000.
Espoo, Finland.

combination of the two, and that the additional capacity is to be calculated based on 0.18 L/s per m^2 of interior floor space. The standard specifically states that this additional capacity shall be in addition to any openable window area. A number of different systems are being used in the U.S. to meet these requirements. One of the most common is an outdoor air intake connected to the air distribution system return duct that brings in ventilation air whenever the forced-air distribution fan operates. Another common approach is the use of a whole house exhaust fan, with or without passive inlet vents installed in the window frames.

Based on a review of the literature on ventilation in U.S. manufactured homes and discussions with individuals in the field, the following issues were identified as relevant to the study:

- Validity of the 0.25 h^{-1} assumption for infiltration
- Impact and effectiveness of an outdoor air inlet to the furnace return
- Impact and effectiveness of whole house exhaust fan with passive inlet vents
- Impact and effectiveness of whole house exhaust fan without passive inlet vents
- Location of whole house exhaust fan in the main living area versus the bathroom

In order to address these issues, simulations were performed in a manufactured house using the multizone airflow model CONTAM [4]. The house model includes the effects of exterior envelope leakage, interior partitions, forced-air distribution and associated duct leakage, exhaust fan operation and outdoor weather.

SUMMARY OF SIMULATION RESULTS

The airflow simulations focused on building ventilation rates relative to the requirements in the MHCSS. Additional simulations and analyses were performed to better understand the airflow characteristics of the simulated house, including: pressurization tests to determine the airtightness of the building envelope; airflow patterns between the major volumes of the house; effective air change rates as a measure of the indoor air quality impacts of different ventilation approaches; age of air to characterize outdoor air distribution to the different zones of the house; and, energy consumption associated with the different ventilation scenarios. The simulations did not address contaminant concentrations in the house or occupant exposure to contaminants. While there are a number of indoor air quality issues of interest in manufactured housing, such as moisture and formaldehyde levels, contaminant analysis was beyond the scope of this project.

In order to understand the impacts of fan operation and interior door position on building air change rates, steady-state airflow simulations were performed for several different conditions. Table 1 presents these air change rates, all of which correspond to an indoor-outdoor air temperature difference of 20°C and zero wind speed. At this temperature difference and wind speed, the house has an air change rate of 0.28 h^{-1}. Operating both bath fans, or the kitchen exhaust fan, raises the air change rate to about 0.7 h^{-1}. Due to the supply duct leak into the crawl space, operating the forced-air fan depressurizes the building, increasing infiltration into the building and yielding an air change rate of 0.55 h^{-1} with all exhaust fans off and interior doors open. The supplemental ventilation strategies investigated in this study increase the air change rate of the house significantly. With an outdoor air inlet duct on the forced-air return, the air change rate is about 0.7 h^{-1}. A whole house exhaust fan in combination with passive inlet vents yields an air change rate of 0.5 h^{-1} with the forced-air fan off and about 0.8 h^{-1} with the fan on. The same whole house exhaust fan without the inlet vents results in an air change rate of 0.44 h^{-1} with the forced-air fan off and 0.79 h^{-1} with it on. Therefore, the supplemental ventilation systems all have the capacity to meet the 0.35 h^{-1} ventilation requirement. Their actual impact in practice depends on how often they are operated and how the operating time is determined.

Table 1. Air Change Rates for Different House and Fan Configurations

Conditions	Air change rate (h^{-1})
Forced-air fan off	
All exhaust fans off	0.28
Both bath fans on; kitchen fan off	0.72
Kitchen fan on; bath fans off	0.73
Forced-air fan on	
All exhaust fans off	0.55
Both bath fans on; kitchen fan off	1.22
Kitchen fan on; bath fans off	1.22
Inlet on forced-air return	
All exhaust fans off	0.65
Both bath fans on; kitchen fan off	1.25
Kitchen fan on; bath fans off	1.25
Passive inlet vents and whole house exhaust in main living area	
Whole house exhaust fan on	0.50
Exhaust and forced air fan on	0.79
Exhaust off and forced-air fan on	0.61
Passive inlet vents and whole house exhaust in bathroom	
Whole house exhaust fan on	0.50
Exhaust and forced air fan on	0.85
Whole house exhaust in main living area, no passive inlet vents	
Whole house exhaust fan on	0.44
Exhaust and forced air fan on	0.79

In order to understand the performance of these different ventilation approaches year-long simulations were conducted in Albany, Miami and Seattle for the following cases:

- Case #1: Envelope leakage only; no fans or ducts in model.
- Case #2: Bath and kitchen exhaust fans on schedules.
- Case #3: Forced-air fan operation based on outdoor temperature.
- Case #4: Outdoor air intake on forced-air return.
  A: Forced-air operation based on outdoor temperature.
  B: Forced-air operation during occupancy.
- Case #5: Whole house exhaust with passive inlet vents.
  A: Exhaust fan in main living area, operated on (Case #2) exhaust fan schedules.
  B: Exhaust fan in main living area, during occupancy.
- Case #6: Whole house exhaust without passive inlet vents.
  A: Exhaust fan in main living area, operated on (Case #2) exhaust fan schedules.
  B: Exhaust fan in main living area, during occupancy.

Case #1 was analyzed to assess building ventilation rates due to envelope leakage alone. Case #2 includes the effects of the exhaust fans operating on occupancy-based schedules of one or two hours per day. Case #3 includes the same scheduled exhaust fans, plus forced-air fan operating for a fraction of each hour based on outdoor temperature. This case reflects the increased building air change rate due to supply duct leakage into the crawl space and represents a baseline case with no supplemental ventilation. Cases #4, #5 and #6 are all different approaches to the supplemental ventilation requirement in the MHCSS. In Case #4, an outdoor air intake duct is connected to the furnace return. Two different schedules for furnace fan operation are employed in Case #4, one based on outdoor air temperature as in Case #3 and one in which the fan also operates continuously whenever the building is occupied. In Case #5 the ventilation system consists a whole house exhaust fan with passive inlet vents incorporated in the bedroom and kitchen/living area windows. This case also includes two schedules of exhaust fan operation, one in which the whole house exhaust fan operates whenever a local exhaust fan would run under the Case #2 schedules and the other in which the fan operates whenever the building was occupied. Case #6 is the same as #5, but without the passive inlet vents. The three cities were selected based on their climates. Albany has a severe winter and a moderate cooling season. Miami is a hot and humid climate, and Seattle has a moderate climate.

Table 2. Summary of Annual Air Change Rates

Case/Condition	ALBANY			MIAMI			SEATTLE		
	Mean air change rate (h^{-1})	Percent of hours < 0.25 h^{-1}	Percent of hours < 0.35 h^{-1}	Mean air change rate (h^{-1})	Percent of hours < 0.25 h-1	Percent of hours < 0.35 h^{-1}	Mean air change rate (h^{-1})	Percent of hours < 0.25 h-1	Percent of hours < 0.35 h^{-1}
1/Envelope leakage only	0.22	56	88	0.10	100	100	0.20	74	99
2/Scheduled exhaust fans	0.27	48	77	0.16	86	91	0.25	64	85
3/Forced-air operating on outdoor temperature	0.34	34	53	0.19	78	90	0.32	33	71
4A/Intake on forced-air, operating on outdoor temperature	0.37	32	46	0.20	73	90	0.33	30	60
4B/Intake on forced-air, occupancy schedule	0.59	13	18	0.51	24	33	0.55	14	24
5A/Passive inlets and whole house exhaust on exhaust schedule	0.41	28	42	0.26	66	84	0.38	24	52
5B/Passive inlets and whole house exhaust on occupancy schedule	0.50	16	29	0.34	38	72	0.47	13	29
6A/ Whole house exhaust (no inlets) on exhaust schedule	0.36	34	52	0.22	78	86	0.34	33	71
6B/ Whole house exhaust (no inlets) on occupancy schedule	0.46	21	35	0.31	52	78	0.43	12	37

Table 2 contains the annual mean air change rates, as well as the percent of hours over the year during which the air change rate is below 0.25 h^{-1} (the infiltration assumption in the MHCSS) and 0.35 h^{-1} (based on ASHRAE Standard 62-1999 [4]). On an annual basis, the envelope infiltration only case (#1) has mean air change rates below the 0.25 h^{-1} in all three cities, and the hourly rate is below this value for 56%, 100% and 74% of the year in Albany, Miami and Seattle respectively. Operating the exhaust fans (Case #2) increases the annual mean air change rates, but there are still a high percentage of hours below 0.25 h^{-1} is all three cities. Case #3 can be considered a baseline case since it includes both local exhaust and forced-air fan operation. The mean air change rate is above the 0.25 h^{-1} in Albany and Seattle. The hourly air change rate is below 0.25 h^{-1} for 34%, 78% and 33% of the year in the three cities. As expected, the mechanical ventilation approaches have higher mean air change rates;

the relevant reference for these cases is 0.35 h^{-1}. The mean air change rates are above 0.35 h^{-1} for almost all of the supplemental ventilation cases in Albany and Seattle, but there are still a significant number of hours during the year below this value. Case #4B has the highest air change rates and the lowest fractions of hours below 0.35 h^{-1} due to the large number of hours during which the ventilation system operates. Case #5B and #6B also have high air change rates and low percentages due to the operating schedule. The means in Miami are all less than or equal to 0.35 h^{-1}, except for Case #4B.

The full report contains a comparison of the predicted air change rates with the limited measurements of air change rates in manufactured homes. The measurements for this comparison are from recently constructed homes, but not homes built to the most demanding energy efficiency standards. And while there are no measured data in the literature that correspond to the exact conditions of the simulations, the data that are available are consistent with the predicted air change rates. The full report also presents age of air values determined to examine the distribution of ventilation air within the building and the level of energy consumption associated with the ventilation approaches for the three cities.

CONCLUSIONS

Validity of the 0.25 h^{-1} assumption for infiltration

Using a single value for a weather-driven infiltration rate is problematic, given the strong dependence of infiltration on weather. As seen in these simulations, the infiltration rates vary by as much as 5 to 1 based on weather variations alone. Including exhaust fan and forced-air fan operation more than doubles the range of variation. Nonetheless, when considering the predicted infiltration rates on an annual basis, the air change rate is below 0.25 h^{-1} for about one-third of the year in Albany and Seattle and for 70 % of the year in Miami. Note that if there were no duct leakage in the house model, these percentages would be significantly higher. Therefore, the assumption of 0.25 h^{-1} for infiltration in modern manufactured homes may be too high, but more importantly it ignores variations due to weather and fan operation.

Impact and effectiveness of an outdoor air inlet to the furnace return

Employing an outdoor air intake duct on the forced-air return duct is effective in raising air change rates and distributing ventilation air throughout the house. However, the impact on the building air change rate is a strong function of the operating time of the forced-air system, which in turn depends on the extent of system oversizing and the use of control strategies such as manual switches and timers. While increased forced-air fan operation provides higher ventilation rates, there is an energy cost associated with increasing fan operation based on the power consumption of the fan itself.

Impact and effectiveness of whole house exhaust fan with passive inlet vents

Whole house exhaust with passive inlet vents provides adequate ventilation in this house and reasonable air distribution, but again the impact is highly dependent on the fan operation schedule. As implemented in this study, these vents were not particularly effective in ventilating the building. Based on the size of the vents relative to the house airtightness, their installation corresponds to a 15% leakier envelope rather than a designed air intake system as they could conceivably be used. Such a system would presumably require a tighter envelope than is typically achieved in practice.

Impact and effectiveness of whole house exhaust fan without passive inlet vents

The simulations with a whole house exhaust fan but without the inlet vents exhibit lower ventilation rates than with the vents as expected. However, the rates are still above the 0.35 h^{-1}

requirement in the MHCSS. Again, the overall impact of the whole house exhaust fan depends on the fan operating schedule. Therefore, given the level of envelope airtightness assumed in these simulations, the passive inlet vents do not appear to be essential to the proper functioning of a supplemental ventilation system based on a whole house exhaust fan.
Location of whole house exhaust fan in the main living area versus the bathroom
For the conditions in this house model, the impact of the whole house fan did not depend much on its location. Whether the fan was in the main living area or a bathroom off the main living area did not have a significant impact on air change rates, outdoor air distribution or building pressures.

RECOMMENDATIONS

While the simulations performed in this study have limitations, there are a number of recommendations that can be made relevant to the construction of manufactured houses and to subsequent versions of the MHCSS. One issue relates to the adequacy of the assumption that these houses have a base infiltration rate of 0.25 h^{-1}. These simulations show that at levels of airtightness consistent with current practice, infiltration rates are often below this value except during colder and windier weather. Also, using a single value ignores the significant variation in infiltration that exists as a function of weather. It may therefore make sense for the MHCSS to consider a more realistic treatment of background infiltration. One potential approach is to use ASHRAE Standard 136 [5] to convert a building airtightness value from a pressurization test to an annual effective air change rate for a given climate.

While the systems studied in this effort and presumably other systems have the capacity to achieve ventilation rates of 0.35 h^{-1} or more, the systems must be operated to achieve these rates. The MHCSS and current practice do not provide sufficient attention to system operation time. This issue could be addressed by specifying that the system operates a sufficient amount of time to increase the average air change rate to a specified level.

The negative impacts of duct leakage are evident in these simulation results, raising ventilation rates well above the required levels and depressurizing the building interior whenever the forced-air system is on. The higher ventilation rates result in an energy penalty, while the depressurization increases the potential for moisture problems in hot, humid climates and can draw contaminants into the conditioned space from the crawl space volume. Instituting design, construction and perhaps commissioning practices that reduce the level of duct leakage is practical with existing technology.

REFERENCES

1. HUD. 1994. Part 3280, Manufactured Home Construction and Safety Standards. U.S. Department of Housing and Urban Development.
2. Persily, A K and Martin, S.R. 2000. A modeling study of ventilation in manufactured houses. National Institute of Standards and Technology Report NISTIR 6455.
3. ASHRAE. 1999. ASHRAE Standard 62-1999, Ventilation for Acceptable Indoor Air Quality, Atlanta: American Society of Heating, Refrigerating, and Air-conditioning Engineers, Inc.
4. Walton, G W. 1997. CONTAM96 users manual. National Institute of Standards and Technology Report NISTIR 6056.
5. ASHRAE. 1993. ASHRAE Standard 136-1993, A Method of Determining Air Change Rates in Detached Dwellings, Atlanta: American Society of Heating, Refrigerating, and Air-conditioning Engineers, Inc.